Title: CRYSTALLOGRAPHIC ANISOTROPY OF THE DE HASS-VAN ALPHEN EFFECT

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CRYSTALLOGRAPHIC ANISOTROPY OF THE DE HAAS-VAN ALPHEN EFFECT

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[3 figures enclosed]

In two previous reports (1) we gave the results of an investigation into the magnetic properties of cadmium, beryllium, magnesium, tin, indium, and bismuth monocrystals. We showed that when the crystallographic axis of symmetry of the highest order is oriented perpendicular to the crystal's axis of suspension and when the field vector, also perpendicular to the axis of suspension, makes various angles with this crystallographic axis then the difference of the main susceptibilities chi's ($\chi_{\parallel} - \chi_{\perp}$) of Cd, Be, Mg, Sn, and In monocrystals varies periodically with the variation in the magnetic field intensity H for low temperatures.

Measurements were conducted with bismuth monocrystals also under other conditions, namely where bismuth's trigonal axis was perpendicular to the field vector (that is, parallel to the axis of suspension) and the field vector could be variously oriented relative to the binary axis in the crystal's basic plane. It was shown that the angular dependence of the above difference of susceptibilities in the basic plane of a bismuth monocrystal is characterized by a 60° period; moreover it was shown that the de Haas - van Alphen effect appears during such a disposition of the crystal in a field.

The magnetic properties of an electron gas in metals at low temperatures have repeatedly been the object of theoretical investigations (2,3).

L. D. Landau (2) has shown that at low temperatures the following relation holds:

$$-\frac{I}{H} = \frac{\sqrt{2}\cdot m^{\frac{3}{2}}\beta^2 E_0^{\frac{1}{2}}}{12\pi^2\hbar^3} + \frac{m^{\frac{1}{2}}kTE_0(\beta H)^{\frac{1}{2}}}{\pi\hbar^3 H^2}\sum_{p=1}^{\infty}(-1)^p \frac{\sin\left(\frac{2\pi pE_0}{\beta H} - \frac{\pi}{4}\right)}{\sqrt{p}\cdot\sinh\left(\frac{2\pi^2 pkT}{\beta H}\right)}$$

where beta is $\beta = e\hbar/mc$; that is, by considering the magnetic properties of an electron gas, Landau has obtained a result which qualitatively explains the de Haas - van Alphen effect.

Application of Landau's theory to crystals leads to an introduction, at least, of the four parameters m_1, m_2, m_3, and E_0, where the first three are the tensor components of the effective electron masses relative to the three mutually perpendicular directions in the crystal and E_0 is the maximum possible energy of the electrons which bring about the de Haas - van Alphen effect in a metal (4,5).

Thus a comparison of theory with experiment is possible only if there is experimental data which permits one correctly and univocally to answer the question of how many of the components m_{ik} must remain in each partial case.

In order to obtain such experimental data obviously one must first of all investigate at low temperatures the anisotropy of magnetic properties in the basic plane of metal monocrystals.

While studying the de Haas - van Alphen effect in zinc, Sydoriak and Robinson (6) investigated the problem of magnetic anisotropy in the basic plane of a zinc monocrystal. Measuring at $T = 4.2^\circ K$ and $H = 5500$ oersteds the conversion diagram (that is, the angular dependence of the above-mentioned difference of chi's $\chi_2 - \chi_1$, where χ_2 is the susceptibility in the direction of a crystal's binary axis and χ_1 is the

susceptibility in the perpendicular direction), they showed that under these conditions one gets $\chi_2 = \chi_1$ and they made this the basis for the selection of just three parameters: $m_1 = m_2$, m_3, E_0 and for the comparison of their experimental data with theory.

The investigation undertaken by us into the anisotropy of magnetic properties in the basic plane of zinc monocrystals permitted us to establish new peculiarities of the de Haas - van Alphen effect in the metal zinc.

The difference of susceptibilities, as in all previous cases, was measured relative to the force couple acting on a crystal suspended by a thin elastic filament in a homogeneous magnetic field. The relative position of the axis of suspension, vector $\vec{H}$, and crystallographic axis was such that the axis of symmetry of the highest order was perpendicular to $\vec{H}$ and parallel to the axis of suspension, but the field vector being located in the basic plane was able to make different angles with the binary axes.

Investigations were carried out with zinc and beryllium monocrystals at low temperatures of liquid hydrogen and helium in fields from 3000 to 14500 oersteds. At 20.4°K existed complete anisotropy of the magnetic properties in the basic plane of zinc monocrystals; up to $H = 14500$ oersteds the force couple equaled zero for any orientation of the field vector relative to the binary axes.

However, investigations at low temperatures of liquid helium have led to a new result. Figure 1 shows the conversion diagram of a zinc monocrystal measured at 4.2°K in a field H=14230 oersteds. As is obvious from the figure, at low temperatures of liquid helium the force couple acting upon a crystal depends in a very complex manner upon the angle phi φ' between the field vector and one of the binary axes; in this case, as in the case of investigations with bismuth, the angular dependence of the force couple is characterized by a 60° period.

Besides the conversion diagram, the dependence of $\chi_2 - \chi_1$ upon the magnetic field strength was also investigated for a similar arrangement of zinc monocrystals. The difference of susceptibilities varies periodically with the variations in the magnetic field intensity; in this case both the anisotropy of magnetic properties and the de Haas - van Alphen effect appear in the basic plane at 4.2°K, starting at H = 9500 oersteds. The period of oscillations of $\Delta\chi$ is very small: in a 10500-oersted field the period equals 180 oersteds and in a 14200-oersted field it reaches 400 oersteds. As we recall, if zinc's main crystallographic axis is perpendicular to the axis of suspension, then the period of oscillations in a 10000-oersted field is more than 2000 oersteds.

The results of measurements, obtained in this work, with zinc testify to the incompleteness of the theoretical handling of experimental data which (i.e. handing) was undertaken by Sydoriak and Robinson.

The period of oscillations of the difference in susceptibilities for any orientation of a crystal in a field is characterized by the quantity $2\pi E_0 / \beta H$, where beta β is a function of the parameters m_{ik} and of the angles between the field vector and the crystallographic axes. In the case of zinc, one must, when using not three but at least four parameters m_1, m_2, m_3, E_0 in the most general case, make a comparison with theory and take into account that the phenomenon has a periodicity of 60° in the basic plane.

The next object of investigations was beryllium. At 78°K exists complete isotropy of magnetic properties in the basic plane of the beryllium monocrystal. Even at 20.4°K, however, the picture is considerably complicated. Figure 2 shows the conversion diagram of a beryllium monocrystal. Obviously, lowering of the temperature to 20.4°K reveals a sudden anisotropy of magnetic properties in the basic plane of this metal (i.e. beryllium) too.

The force couple C depends in a very complex manner upon angle; hence it is very much like the situation with Bi and Zn, and beryllium's angular dependdence of the force couple in the basic plane is also characterized by a 60° period. The angle $\varphi' = 0°$ corresponds in both figures to the case where the field vector is parallel to either of the binary axes of the crystal. We note that the force couple is converted to zero again not only through $\pm$ 60° but also at a half period, that is, through $\pm$ 30°.

Further lowering of the temperature complicates still more the angular dependence of the force couple. Figure 3 shows part of a conversion diagram measured at T = 4.2°K and H = 9500 oersteds.

It is already obvious from a study of the conversion diagram shown in figure 2 that the difference of susceptibilities $\Delta\chi = \chi_2 - \chi_1$ in the basic plane of a beryllium monocrystal varies periodically in dependence on the magnetic field strength. Actually, curve 1 is measured at H = 13720 oersteds, and curve 2 at H = 14510 oersteds; in both of these cases the force couple (consequently $\Delta\chi$ also) changes it sign for both of these values of the angle phi φ'.

In beryllium monocrystal's basic plane the angular dependence of the force couple and the periodic nature of the variation of $\Delta\chi$ with the variation of H are very clearly apparent even at 20.4°K in a field around 10000 oersteds. The period of oscillations is large: in a 12000-oersted field the period is 900 oersteds.

Measurements with beryllium and zinc monocrystals were carried out on several specimens, and in all cases the results were completely identical.

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[3 figures follow]

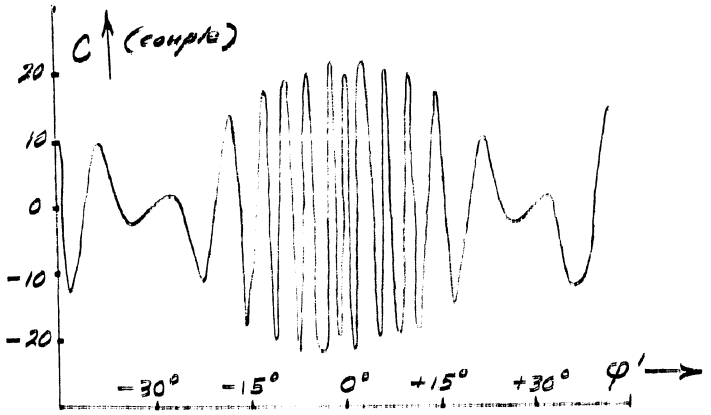

Figure 1. The conversion diagram; that is, the dependence of the force couple acting upon a zinc monocrystal suspended in a homogeneous magnetic field by a fine elastic filament upon the angle between the field vector and the crystal's binary axis. The crystallographic axis of the sixth order is perpendicular to $\vec{H}$. T=4.2° K and H=14230 oersteds.

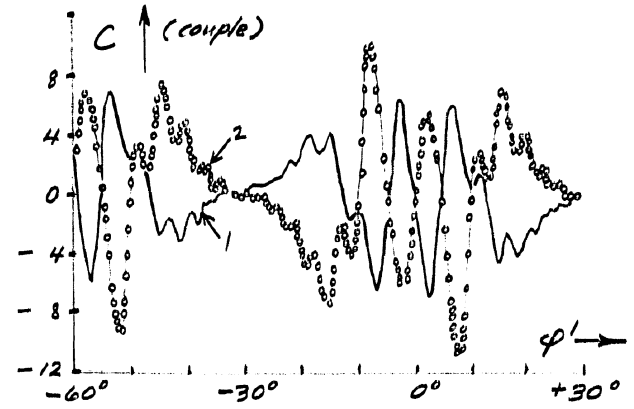

Figure 2. Conversion diagram in the basic plane of a beryllium monocrystal. T=20.4°K . Curve 1 : H=13720 oersteds, curve 2 : H=14510 oersteds.

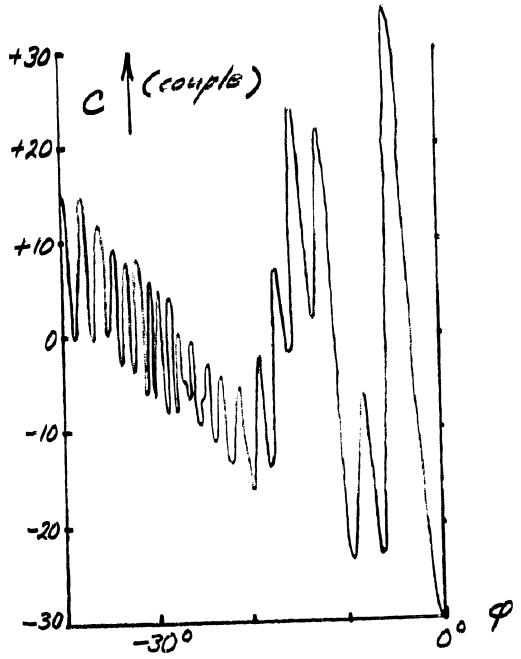

Figure 3. The conversion diagram in the basic plane of a beryllium monocrystal. T=4.2°K and H=9500 oersteds.